Influence of Nonlinear Shear Modulus Change of Elastomeric Shell of a Composite Tractive Element with a Damaged Structure on its Stress State

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http://doi.org/10.29227/IM-2023-01-18

Submission date: 08-02-2023 | Review date: 27-03-2023

Abstract

Purpose. Determination of a dependency of a stress state for composite elastomer-cable tractive element with a broken structure on a nonlinear dependency of shear modulus on deformations in the elastomeric shell.
Methods. Analytical solution of a model of a composite tractive element with disturbed structure and a deformation-dependent shear modulus of an elastomeric shell.
Findings. Algorithm for determining a stress state of a composite tractive element with broken structure and a deformation-dependent shear modulus.
Scientific novelty. Character of dependency for a stress state of a composite tractive element on a nonlinear dependency of shear modulus on deformations.
Practical significance. A possibility to determine the dependency of a stress state of a composite elastomer-cable tractive element on a nonlinear shear modulus allows considering the effect of this phenomenon on the tractive element strength and ensures an increase of its operational safety.

Keywords: *mineral resources, mining, lifting and transporting complexes, composite tractive element, damaged structure, elastomeric shell, stress state, analytical solution*

1. Introduction

Continuous improvement of technical systems in the fields of mining technologies [1–9], transportation and hoisting [10–12], deep-sea mining [13, 14], and dynamics of technical systems [15–19] facilitate wider and more thorough development of analytical and computational simulation methods of processes and phenomena occurring within the systems. Currently, researchers in many countries are conducting complex scientific studies aimed at developing methods and means of modernizing lifting and transporting complexes with the aim of increasing operational efficiency and safety of mining transport equipment. Composite elastomer-cable tractive elements, in particular rubber-cable ropes (also known as steel cord belts), are widely used in hoisting and transporting machines [20–24]. At the same time, these tractive elements have significant lengths. Conveyor belts of a closed shape are created by connecting ends of belts. Cables at belt ends in such connections are not mechanically connected and interact through rubber layers. Damage accumulates in ropes during use. One type of damage is rupture of one of reinforcing elements (cables). Rupture of continuity of cables and presence of non-continuing cables, in accordance with the Saint-Venant's principle, are sources of disturbance of a stress-strain state in a rope (belt).

2. State of question and statement of research problem

Rope strength in the cross-section of cable breakage is much lower [25–27], it is also lower in butt joints [28]. In paper [29], it is suggested to determine a stress-strain state of spatial structures reinforced with parallel elements by means of electrical modelling. A method of determining characteristics of materials with a system of regularly arranged parallel reinforcing elements is suggested in the article [30]. The papers [31–40] are devoted to investigation of features of a rope (belt) stress state, considering its interaction with structural elements of a machine. Experience indicates that there is a nonlinear dependency of stresses in elastic materials on their deformations, and rubber is no exception to this. Rubber layers in rubber-cable ropes ensure the connection of cables, determine a mechanism of redistribution of forces between the cables, which affects the operational characteristics of the entire rope. In these papers, the issue of a nonlinear law of rubber deformation is not considered. At the same time, it constitutes an actual scientific and technical problem of considering the specified feature during the design and continuous control of the condition of hoisting and transporting machines with a rubber-cable tractive element. The solution allows considering the influence of deformation character in rubber on rope strength and provides a possibility of increasing operational safety of rubber-cable ropes (belts).

Generally, the dependency graph of stresses on deformations has a shape of a curved line. The main factor in the occurrence of shear stresses in rubber layers of a rope or belt is breakage of continuity of cables. Discontinuity of cables occurs in the event of cable breakage and in butt joints of rub-

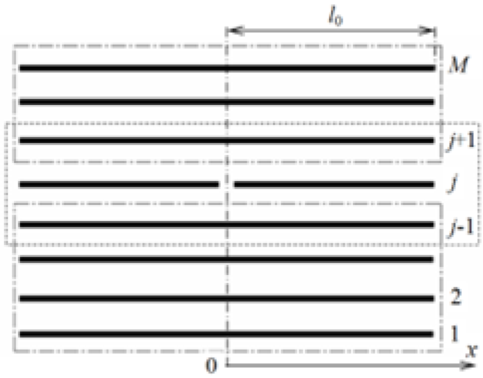

Fig. 1. Rope part with a broken cable
Rys. 1. Część liny z pękniętym kablem

ber-cable ropes and belts. In butt-joint connections, no cables at both ends of the connected belts continue. A cable break or a cable end is a source of stress-strain state disturbance in a rope (belt). Well-known studies [26] indicate that deformations of rubber take place practically only in the layers adjacent to the broken cable. Deformation values are maximum in the cross-section of cable continuity breakage and decrease exponentially with increasing distance from the specified cross-section.

3. Presentation of main research

Determining a stress-strain state considering the specified character of deformation changes and considering the nonlinear dependency of shear displacements on rubber shear stresses is a complex mathematical problem. Let's simplify it. Assume that the dependency of rubber shear stresses on its deformations is piecewise linear and consists of two parts. As in the studies mentioned above, we assume that the cables deform like rods. Rubber is subjected only to shear stress. The rope is infinitely long. It has M cables and is loaded with a tensile force P. The cable numbered j has a continuity breakage. The cross-section with the breakage is at a considerable distance from the rope edges. Rubber shear modulus of layers adjacent to the damaged cable at lengths l0 is different from the corresponding rubber shear modulus of the remaining layers. The linear size l0 is much smaller than the rope length, on which the stress state is changed because of a cable breaking. Direct the coordinate axis along the rope. Its beginning (x = 0) is located at the point where the cable breaks. Since the cross-section (x = 0) is a cross-section of symmetry, the displacements of cables are symmetrical. At the same time, the cross-sections of all cables except the ends of the broken cable do not move. A gap is formed between the ends of the damaged cable. Let's denote the displacement of the end of the damaged cable U₀.

Let's single out a part of length $l_0 (0 \le x \le l_0)$. Consider it the first one. Consider the part for which $x > l_0$ the second part. The first part of the rope is divided into three stripes with an unchanged number of cables in each. Include stripes that do not have a broken cable into the structure of the two extreme stripes. Give them numbers one and three. The rope part with the broken cable and the cables adjacent to it will be included in the structure of the second stripe (Fig.1).

Consider the specified stripes as separate belts. A characteristic feature of such rope stripes is that the properties of elastic material between the rope stripes do not change. Shear modulus of rubber in layers between cables is not variable in our case. This allows using the conditions of their equilibrium and the form of solutions for stripes [26], considering the number of cables in stripes and properties of elastic shell. Let's make expressions that allow determining the internal forces in cables and their displacements. Write down the expressions for the extreme stripes in similar forms. In the expressions, we will use additional indices to assign the parameters to one or another rope stripe. Take into account that cross-sections of cables of the extreme stripes do not move when (x = 0).

For a rope stripe with cable numbers

$$p_{1,i} = E\,F \sum_{m=1}^{j-2} A_m \left(e^{\beta_{1,m} x} + e^{-\beta_{1,m} x} \right) \beta_{1,m} \cos\left(\mu_{1,m} \left(i - 0.5 \right) \right) + P, \qquad (1)$$

$$u_{1,i} = \sum_{m=1}^{j-2} A_m \left(e^{\beta_{1,m} x} - e^{-\beta_{1,m} x} \right) \cos\left(\mu_{1,m} \left(i - 0.5 \right) \right) + \frac{P\,x}{E\,F}, \qquad (2)$$

where i is cable number in the first stripe (1 ≤ i ≤j‑2); A_m, B_m are integration constants; E, F are, respectively, reduced tensile modulus of elasticity and cross-sectional area of a cable in a rope (belt); $\beta_{1,m} = \sqrt{\frac{2 G_0 b}{(h-d) E F} [1 - \cos(\mu_{1,m})]}$; h is distance between the cables; b is rope thickness; d is cable diameter; G is shear modulus of elastic (rubber) layer connecting the cables.

For the second rope stripe with cable numbers (j‑1 ≤ i ≤ j+1)

$$p_{2,i} = E\,F \sum_{m=1}^{2} \left[\left(A_{m+j-2} e^{\beta_{2,m} x} - B_{m+j-2} e^{-\beta_{2,m} x} \right) \beta_{2,m} \cos\left(\mu_{2,m} \left(i - j - 1.5 \right) \right) \right] + P, \qquad (3)$$

$$u_{2,i} = \sum_{m=1}^{2} \left(A_{m+j-2} e^{\beta_{2,m} x} + B_{m+j-2} e^{-\beta_{2,m} x} \right) \cos\left(\mu_{2,m} \left(i - j - 1.5 \right) \right) + \frac{P\,x}{E\,F}, \qquad (4)$$

where $\mu_{2,m} = \frac{\pi m}{3}$; $\beta_{2,m} = \sqrt{\frac{2 G_0 b k}{(h-d) E F} [1 - \cos(\mu_{2,m})];}$,
k is coefficient, which considers the difference in shear modulus of rubber for the second stripe.

For a rope stripe with cable numbers (j+1 ≤ i ≤ M)

$$p_{3,i} = E\;F \sum_{m=1}^{M-j-1} A_{m+j} \left(e^{\beta_{3,m} x} + e^{-\beta_{3,m} x} \right) \beta_{3,m} \cos\left(\mu_{3,m} \left(i - j - 1.5 \right) \right) + P, \qquad (5)$$

$$u_{3,i} = \sum_{m=1}^{M-j-1} A_{m+j} \left(e^{\beta_{3,m} x} - e^{-\beta_{3,m} x} \right) \cos\left(\mu_{3,m} \left(i - j - 1.5 \right) \right) + \frac{P\,x}{E\,F}, \qquad (6)$$

where $\mu_{3,m} = \frac{\pi m}{M - j}$; $\beta_{3,m} = \sqrt{\frac{2 G_0 f(t) b k_G}{(h-d) E F} [1 - \cos(\mu_{3,m})]}$.

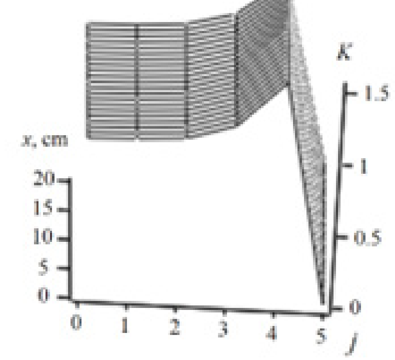

Fig. 2. Dependency of coefficients of uneven distribution of forces among cables with numbers i along the x-axis
Rys. 2. Zależność współczynników nierównomiernego rozkładu sił między kablami o liczbach i wzdłuż osi x

These solutions correspond to the conditions of influence absence of external factors on extreme cables in stripes on the interval ($0 \le x \le l_0$). The cables adjacent to the broken one are included in two stripes – the extreme one and non-extreme one. In the extreme stripes, there are no disturbances in cables adjacent to the broken one, in accordance with solutions of (1), (2) and (5), (6). They are loaded with only evenly distributed forces. Cables in the cross-section x = 0 are immovably fixed. In a general solution, based on the principle of superposition, we add their displacements as cables, which are part of the middle stripe, to displacements of these cables without considering the force of their external load.

The end of the middle cable in the middle stripe is displaced by an unknown amount U_0 under the action of an external force. Let's write the above in a form of a boundary condition for the cross-section x = 0

$$u_{2,i} = U_0 \begin{cases} 0 & i \ne j \\ 1 & i = j \end{cases} \tag{7}$$

According to (7), the law of cable displacements corresponds to the product of displacement of a middle cable and the Dirac function δ. Let's take the Dirac function in a form of a Fourier series on a given segment of cable numbers. From expression (4), we have the following

$$\sum_{m=1}^{2} \left(A_{m+j-2} + B_{m+j-2} \right) \cos\left(\mu_{2,m} (i-0.5) \right) = \frac{2}{3} U_0 \sum_{m=1}^{2} \cos\left(\frac{3}{2} \mu_{2,m} \right) \cos\left(\mu_{2,m} (i-0.5) \right), \quad (i = 1,2,3). \tag{8}$$

From where

$$B_{m+j-2} = \frac{2}{3} U_0 \cos\left(1.5\mu_{2,m}\right) - A_{m+j-2}, \quad (m = 1,2). \tag{9}$$

From the condition that a load on the broken cable in the cross-section of breakage is equal to zero from expression (3) we have

$$U_0 = \frac{3P}{2\beta_{2,m} E F \cos^2\left(1.5\mu_{2,m}\right)} + 3\frac{A_{m+j-2}}{\cos\left(1.5\mu_{2,m}\right)}. \tag{10}$$

Accordingly, expression (9) takes the form

$$B_{m+j-2} = \frac{P}{\beta_{2,m} E F \cos\left(1.5\mu_{2,m}\right)} + 2A_{m+j-2}. \tag{11}$$

Expressions of forces (3) and displacements (4) considering the general numeration of cables in the cross-section of a rope take the following forms

$$p_{2,i} = E F \sum_{m=1}^{2} \left[\left(A_{m+j-2} \left(e^{\beta_{2,m} x} - 2e^{-\beta_{2,m} x} \right) \beta_{2,m} - \frac{P e^{-\beta_{2,m} x}}{\cos\left(1.5\mu_{2,m}\right)} \right) \times \cos\left(\mu_{2,m} (i-j-1.5) \right) \right] + P, \tag{12}$$

$$u_{2,i} = \sum_{m=1}^{2} \left[\left(A_{m+j-2} \left(e^{\beta_{2,m} x} + e^{-\beta_{2,m} x} + 0.5 \right) + \frac{P\left(e^{-\beta_{2,m} x} + 0.5 \right)}{\beta_{2,m} E F \cos\left(1.5\mu_{2,m}\right)} \right) \times \cos\left(\mu_{2,m} (i-j-1.5) \right) \right] + \frac{P x}{E F}. \tag{13}$$

Using (1), (2), (5), (6), (12), (13), we write down the values of forces and displacements as single functions on the finite axis of cable numbers

$$p_i = \frac{2 E F}{M} \sum_{n=1}^{M-1} \rho_n(x) \cos\left(\mu_n (i-0.5) \right) + P, \tag{14}$$

where $\mu_n = \dfrac{\pi n}{M-1}$;

$$\begin{aligned} \rho_n(x) = {} & \sum_{\chi=1}^{j-1} \sum_{m=1}^{j-2} \left[A_m \left(e^{\beta_{1,m} x} + e^{-\beta_{1,m} x} \right) \beta_{1,m} \cos\left(\mu_{1,m} (\chi-0.5) \right) \cos\left(\mu_n (\chi-0.5) \right) \right] + \\ & + \sum_{\chi=1}^{3} \sum_{m=1}^{2} \left[\left(A_{m+j-2} \left(e^{\beta_{2,m} x} - 2e^{-\beta_{2,m} x} \right) \beta_{2,m} - \frac{P e^{-\beta_{2,m} x}}{E F \cos\left(1.5\mu_{2,m}\right)} \right) \times \cos\left(\mu_{2,m} (\chi-0.5) \right) \cos\left(\mu_n (\chi+j-2.5) \right) \right] + \\ & + \sum_{\chi=1}^{M-j-1} \sum_{m=1}^{M-j-1} \left[A_{m+2} \left(e^{\beta_{3,m} x} + e^{-\beta_{3,m} x} \right) \beta_{3,m} \times \cos\left(\mu_{3,m} (\chi-0.5) \right) \cos\left(\mu_n (\chi+j-0.5) \right) \right]. \end{aligned} \tag{15}$$

$$u_i = \frac{2}{M} \sum_{n=1}^{M} \upsilon_n(x) \cos\left(\mu_n (i-0.5) \right) + \frac{P x}{E F},$$

where

$$\begin{aligned} \upsilon_n(x) = {} & \sum_{\chi=1}^{j-1} \sum_{m=1}^{j-2} \left(A_m \left(e^{\beta_{1,m} x} - e^{-\beta_{1,m} x} \right) \cos\left(\mu_{1,m} (\chi-0.5) \right) \cos\left(\mu_n (\chi-0.5) \right) \right) + \\ & + \sum_{\chi=1}^{3} \sum_{m=1}^{2} \left(\left(A_{m+j-2} \left(e^{\beta_{2,m} x} + e^{-\beta_{2,m} x} \right) + \frac{P e^{-\beta_{2,m} x}}{\beta_{2,m} E F \cos\left(1.5\mu_{2,m}\right)} \right) \times \cos\left(\mu_{2,m} (\chi-0.5) \right) \cos\left(\mu_n (\chi+j-2.5) \right) \right) + \\ & + \sum_{\chi=1}^{M-j-1} \sum_{m=1}^{M-j-1} \left(A_{m+2} \left(e^{\beta_{3,m} x} - e^{-\beta_{3,m} x} \right) \cos\left(\mu_{3,m} (\chi-0.5) \right) \cos\left(\mu_n (\chi+j-0.5) \right) \right). \end{aligned}$$

Expressions (14), (15) are obtained for the first part of the rope for ($0 \le x \le l_0$). In cross-section $x = l_0$ the considered part of the rope interacts with its second part. Write expressions of forces ($p_{0,i}$) and displacements ($u_{0,i}$) for the second part in the forms [26]. At the same time, we consider that an infinite increase in the value of the x-coordinate cannot lead to an infinite increase in the loading forces of cables and their displacements

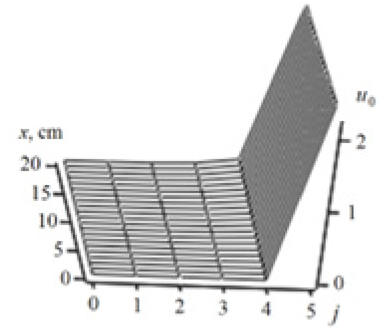

Fig. 3. Dependency of a product of rigidity and displacements of cables with numbers i along the x-axis

Rys. 3. Zależność iloczynu sztywności i przemieszczeń lin o liczbach i wzdłuż osi x

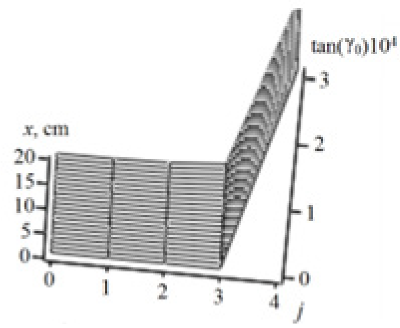

Fig. 4. Dependency of tangents of shear angles of elastic shell between cables with numbers j along the x-axis relative to its average value

Rys. 4. Zależność tangensów kątów ścinania powłoki sprężystej między kablami o numerach j wzdłuż osi x względem jej wartości średniej

$$p_{0,i} = -EF\sum_{n=1}^{M-1} B_{0,n} e^{-\beta_n^* x}\beta_n^* \cos\left(\mu_n (i-0.5)\right) + P, \qquad (16)$$

$$u_{0,i} = \sum_{n=1}^{M-1} B_{0,n} e^{-\beta_n^* x} \cos\left(\mu_n (i-0.5)\right) + \frac{Px}{EF}, \qquad (1 \le i \le M), \qquad (17)$$

where

$$\beta_n = \sqrt{\frac{2G_0 b}{(h-d)EF}[1-\cos(\mu_n)]}.$$

At the same time, in cross-section x=l₀ the conditions of joint deformation of rope parts must be fulfilled

$$p_{0,i} = p_i, \qquad (18)$$

$$u_{0,i} = u_i \qquad (19)$$

From expressions (14), (15) and conditions (18), (19), we have equalities

$$B_{0,n} e^{-\beta_n^* l_0} = -\frac{2}{M\beta_n^*}\rho_n \qquad (x = l_0), \qquad (20)$$

$$B_{0,n} e^{-\beta_n^* l_0} = \frac{2}{M}\upsilon_n \qquad (x = l_0). \qquad (21)$$

Subtract (21) from (20). We get a system of N – 1 equations

$$\sum_{\chi=1}^{j-1}\sum_{m=1}^{j-2}\left(\begin{matrix} A_m\left(e^{\beta_{1,m} l_0}\left(1+\frac{\beta_{1,m}}{\beta_n^*}\right) - e^{-\beta_{1,m} l_0}\left(1-\frac{\beta_{1,m}}{\beta_n^*}\right)\right)\times \\ \times\cos\left(\mu_{1,m}(\chi-0.5)\right)\cos\left(\mu_n(\chi-0.5)\right)\end{matrix}\right) +$$
$$+\sum_{\chi=1}^{3}\sum_{m=1}^{2}\left(\begin{matrix}\left(\begin{matrix} A_{m+j-2}\left(e^{\beta_{2,m} l_0}\left(1+\frac{\beta_{2,m}}{\beta_n^*}\right) + e^{-\beta_{2,m} l_0}\left(1-2\frac{\beta_{2,m}}{\beta_n^*}\right)\right) + \\ +\frac{Pe^{-\beta_{2,m} l_0}}{EF\cos\left(1.5\mu_{2,m}\right)}\left(\frac{1}{\beta_{2,m}}-\frac{1}{\beta_n^*}\right)\end{matrix}\right)\times \\ \times\cos\left(\mu_{2,m}(\chi-0.5)\right)\cos\left(\mu_n(\chi+j-2.5)\right)\end{matrix}\right) + \qquad (22)$$
$$+\sum_{\chi=1}^{M-j-1}\sum_{m=1}^{M-j-1}\left[\begin{matrix} A_{m+2}\left(e^{\beta_{3,m} l_0}\left(1+\frac{\beta_{3,m}}{\beta_n^*}\right) - e^{-\beta_{3,m} l_0}\left(1-\frac{\beta_{3,m}}{\beta_n^*}\right)\right)\times \\ \times\cos\left(\mu_{3,m}(\chi-0.5)\right)\cos\left(\mu_n(\chi+j-0.5)\right)\end{matrix}\right].$$

The solution of obtained system of equations (22) allows determining the unknown constants and internal loading forces of cables, and their displacements. The known displacements make it possible to determine tangential stresses in material of the elastic shell located between the cables, which are directly proportional to the tangent of its shear angle

$$\tan(\gamma_i) = \frac{u_i - u_{i+1}}{h}, \qquad (1 \le i < M). \qquad (23)$$

With the use of obtained dependencies, stress-strain state indicators are determined for a rope type RCB-3150 consisting of six cables. The sixth of them is broken. The area length l0 is assumed equal to 0.1 m. Coefficient of change of shear modulus is 0.5. The results of calculations are given below. Figure 2 shows the dependency of a ratio of internal loads in cables to the average load (coefficients of uneven distribution of forces among the cables) along the x-axis.

Let's pay attention to the fact that x = 10 cm corresponds to the boundary of rope parts. Presence of a boundary that divides the rope into parts with different values of shear modulus practically does not affect distribution of forces among the cables. The loads on the broken cable increase as the x-coordinate increases from zero. Cable adjacent to the broken one is loaded more than the other cables. Its maximum internal load – the coefficient of uneven distribution of forces occurs in the cross-section of cable breakage. This value reaches 1.53. The value of coefficients of unevenness decreases with a cable distance from the one adjacent to the broken one and with distance from the cross-section of breakage. We compare the values of force concentration coefficients for cases of linear and assumed nonlinear dependency of shear modulus on deformations. The analysis of results shows that an increase in

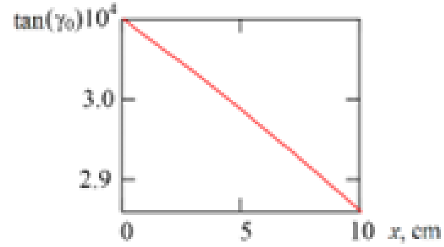

Fig. 2. Dependency of coefficients of uneven distribution of forces among cables with numbers i along the x-axis

Rys. 2. Zależność współczynników nierównomiernego rozkładu sił między kablami o liczbach i wzdłuż osi x

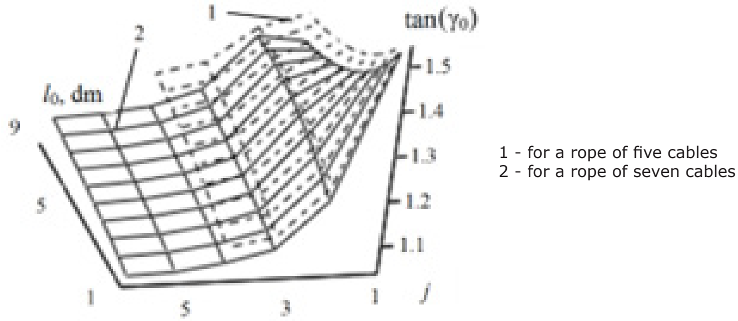

Fig. 6. Coefficients of force distribution among cables in ropes with a different number of cables

Rys. 6. Współczynniki rozkładu sił między kablami w linach o różnej liczbie kabli

the area of action of the reduced shear modulus leads to an increase in the maximum value of coefficient of uneven distribution of forces among cables. Therefore, when rope part length is 100 mm, the excess of the force concentration coefficient reaches 15%. For a rope part length of 500 mm it reaches 5%. For the infinite growth of the area of lower rigidity of rubber layers connecting the damaged cable with its adjacent cables, the coefficient of uneven distribution of forces infinitely approaches the corresponding coefficient obtained without considering the nonlinear law of dependency of shear modulus on the mutual shear of cables.

Butt joints have cross-sections, in which the number of cables changes, just as it changes in a rope with a broken cable. Such a change in the number of cables leads to a mutual displacement of cables in a rope cross-section. The cable with a breakage moves the most relatively to the adjacent ones. This is observed both in butt joints and in a rope with a broken cable. Accordingly, the obtained results can be extended to butt joints. Considering the nonlinearity of rubber shear deformations is expedient because the lengths of butt joint steps are smaller than the sizes of areas of stress disturbance from local change in the butt joint design.

The ratio between displacements of cables numbered i and a displacement of the broken cable in the cross-section of its breakage are shown in the Figure 3.

The displacements of cables shown in Figure 3 in the cross-section x = 0 correspond to the assumed form of displacements. As the distance from the cross-section of cable breakage increases, the character of curvature of the rope cross-sections changes – the amount of curvature decreases. The established distribution of displacements made it possible to find distributions of the tangents of shear angles of elastic material between cables. Figure 4 shows the tangents of shear angles of elastic shell between cables with numbers i along the x-axis, relative to its average value.

The shear of cables occurred practically only between the broken cable and the one adjacent to it. At the same time, rigidity of rubber between the specified cables in a rope part ($0 \le x \le 10$mm) is lower than the rigidity of other layers. The maximum mutual shear does not change significantly on the area ($0 \le x \le l_0$) (Fig. 5).

Figure 5 shows a slight deviation of tangents of shear angles of elastic shell from the average value.

In practice, ropes of various designs are used, including with a different number of cables. Figure 6 shows the dependency of distribution of force distribution coefficients among cables in ropes with different numbers of cables.

The figure shows that an increase in a number of cables in a rope does not significantly affect the maximum values of internal loading forces of cables. The analysis of expressions (19), (20) shows that the increase in the number of cables in a rope over ten practically does not affect the value of maximum stresses in a case of breakage of the extreme cable. In case of breakage of the middle cable, the maximum force in adjacent cables practically does not depend on their number when there are more than sixteen of them.

4. Conclusions

By analytically solving a model of a rubber-cable tractive element with a broken structure and nonlinear deformation-dependent rubber shear modulus, the dependencies of changes in a stress state of a rubber-cable tractive element with a broken structure in a form of a cable breakage are established.

In a process of solving the model, an algorithm for determining a stress state of a rubber-cable tractive element with a broken structure is formulated. A mechanism for changing a stress state of a rubber-cable rope is established, considering the nonlinear deformation-dependent shear modulus of rubber.

It is established that an increase in area of action of the reduced shear modulus leads to an increase in the maximum value of a coefficient of uneven distribution of forces between the cables. With infinite growth of area of lower rigidity of rubber layers connecting the broken cable with the adjacent cables, the coefficient of uneven distribution of forces infinitely approaches the corresponding coefficient determined without considering the nonlinear law of the dependency of shear modulus on deformations.

The obtained results can be extended to butt joints. Considering the non-linearity of rubber shear deformations is expedient because lengths of butt joint steps are smaller than sizes of areas of stress disturbance from a local change in butt joint design.

Considering the nonlinear deformation-dependent shear modulus of rubber provides an opportunity to specify the prediction of a rope stress state with a continuity breakage of cables, increase safety and operational reliability of rubber-cable tractive elements.

The results are obtained using well-known methods of theory of composite materials of a rubber-cable rope model and its solution using analytical methods. The model considers the nonlinear law of rubber deformation. This allows considering the obtained results as sufficiently reliable and as such that they clarify the idea of a mechanism of deformation of rubber-cable ropes and belts.

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Badanie wpływu kompensacji na stabilność górotworu oraz jakość wydobywanej rudy

Artykuł przedstawia studium i analizę funkcjonalną wymagań światowego przemysłu metalurgicznego co do jakości rud żelaza w podziemnych kopalniach Ukrainy. Stwierdzono zależności wpływu kształtu i parametrów przestrzeni kompensacyjnych na ich stateczność i wskaźniki jakości rudy. Udowodniono, że komora wyrównawcza w kształcie trapezu pionowego charakteryzuje się największą stabilnością i jest stabilna w zakresie wszystkich rozważanych głębokości, nawet w rudach o twardości 3–5 punktów. Mniejszą stateczność wykazuje komora kompensacji pionowej o kształcie sklepionym z niewielkimi spadkami w przyczółku sklepienia komory w rudach o twardości 3–5 punktów na głębokości 2000 m. Komora z opadami o różnym natężeniu występuje w dolnej części nachylonych odsłonięć namiotu w rudach o twardości 3–5 punktów na głębokości 1750 m lub większej. Pomieszczenie kompensacji poziomej ma najmniejszą stateczność; spadki występują w rudach o twardości 3–5 punktów na głębokości 1400 m, a na głębokościach 1750–2000 m pozostają stabilne tylko w rudach twardszych. Stwierdzono, że zastosowanie komór kompensacyjnych o dużej stabilności umożliwia osiągnięcie ich maksymalnej objętości, zwiększenie ilości wydobywanej czystej rudy, zmniejszenie jej rozrzedzenia, poprawę jakości wydobywanej masy rudy, a co za tym idzie, wzrost jej ceny i konkurencyjności rynkowej.

Słowa kluczowe: *surowce mineralne, kompleksy wydobywcze wyciągowe i transportowe, kompozytowy element trakcyjny, uszkodzona konstrukcja, powłoka elastomerowa, stan naprężeń, rozwiązanie analityczne*